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Applications of Endothermic Reaction Technology to the High Speed Civil Transport

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INTRODUCTION

The HSCT engine will operate at near maximum temperature and stress levels throughout supersonic cruise. Therefore, although the cycle temperatures are not much different from current generation engines, the time at temperature (hot time) and stress will be up to 30 times greater. Advanced materials development programs are giving rise to new nickel alloys for the compressor and turbine disks, new nickel and thermal barrier coating (TBC) systems for the turbine airfoils, and ceramic matrix composites (CMC) for the combustor liner and exhaust nozzle. Current efforts have provided confidence in the ability to meet the minimum acceptable life goals for those parts which have been analyzed in detail. However, an increase in reliability and durability over the minimum acceptable would have a significant payoff.

A fuel-cooled thermal management system would prove very valuable when used to reduce the temperature of the turbine airfoil and disk cooling air. Compressor bore cooling is also an attractive application. In either case, disk radial temperature profiles (i.e., thermal stresses) need to be considered and the level of cooling selected upon consideration of a possible impact on weight. Similarly, an endothermic reaction system might prove beneficial for cooling the bearing compartments or electronic control systems, with the waste heat absorbed by the fuel being returned to the cycle, improving performance. In addition, injection and combustion of supercritical vaporized fuel would eliminate the current requirement for recirculating fuel back to the tank. Moreover, supercritical preheating and endothermic cracking of the fuel prior to combustion may enable improved mixing, broadened combustion stability, and reduced smoke and NO_X emissions.

HSCT CYCLE ANALYSIS

The baseline engine cycle for powering a Mach 2.4 commercial transport has been selected for this study. The engine is a two-spool turbofan which incorporates a three-stage fan, a five-stage high pressure compressor, a single-stage high pressure turbine, and a two-stage low pressure turbine. The baseline engine cycle is defined as HSCT Engine Cycle 3770.42. All performance data in this paper will be shown as relative to the baseline cycle.

Initial efforts in this study were directed at determining the impact on engine performance of cooling the turbine airfoil and disk with preconditioned compressor bleed air. Analyses of the engine cycle and fuel thermal management system were conducted at the 2.4M/55K cruise condition, which represents the most severe thermal environment, and at the 0.9M/36K subsonic cruise condition.

A conceptual approach for using the endothermic heat sink potential of the fuel was defined, and a preliminary architecture was configured for a corresponding thermal management system. The system is configured to provide means for cooling a portion of the high-pressure compressor discharge air, using part of the engine fuel flow as the coolant. The cooled air is subsequently used to cool the high-pressure-turbine airfoils, with a portion being directed through hollow vanes across the compressor diffuser, into the engine bore.

The specific strategy for using this cooling resource was selected from among the following possibilities:

- Reducing the amount of cooling flow, with constant metal temperature and burner states,
- Reducing the metal temperature, with constant flow and burner states, and
- Increasing the burner temperature/pressure, with constant cooling flow and metal temperature.

These various combinations can result in reduced thrust specific fuel consumption (TSFC), increased engine hot section life, increased engine thrust-to-weight ratio, or combinations of the foregoing. Since increasing burner temperature implies an accompanying increase in NO_x emissions, this option was eliminated from further consideration. Several of these trades have been examined, and the corresponding thermal management system designed. The required analysis for consideration of performance trades involves only the engine cycle, as long as the assumed performance of the thermal management system is achievable.

The initial evaluation of the effect of the thermal management concept was performed at the beginning of cruise, with the engine at maximum power. The extracted compressor bleed air was assumed to be cooled with 80% of the engine fuel flow, yielding an air temperature reduction of approximately 200 F in the turbine cooling air. This level of cooling was specified to avoid generating large thermal gradients in the turbine airfoils that would increase the stress and require a corresponding increase in component weight. Preliminary analysis indicated that this is an achievable cooling goal.

Table 1 shows the effect of fuel cooling on HSCT engine performance for two possible approaches, corresponding respectively to increased turbine lifetime and improved fuel economy. In both cases, the cooling air temperature is lowered 200 F, the high-pressure-turbine (HPT) rotor inlet temperature is maintained constant, and the fuel temperature and heating value are increased (due to cracking reactions), permitting a reduction in the fuel flow rate. For increased lifetime, the amount of HPT cooling is maintained at the baseline flow rate, resulting in lower metal temperatures. For improved fuel economy, the HPT cooling is reduced to 75% of the baseline flow, while metal temperatures and, therefore, turbine life remain unchanged from the baseline engine.

Table 1 - Effect of Fuel Cooling on HSCT Engine Performance at 2.4M/55K Supersonic Cruise (Change from Baseline)

	Increased Lifetime	Improved Fuel Economy
HPT Cooling Air, % of Baseline	100	75
HPT Cooling Air Temperature Reduction, F	200	200
Fuel Heating Value Increase, Btu/lb	370	270
Change in Combustor Exit Temp. (ΔT_4), F	+20	-35
Fuel Heating Value Change, %	+ 2.0	+ 1.4
Fuel Flow Change, %	- 0.4	- 2.7
Net Thrust Change, %	- 0.3	- 1.9
TSFC Change, %	- 0.1	- 0.7

In the case corresponding to increased lifetime, the enhanced cooling allows the combustor exit temperature (T_4) to be increased by 20 F. There is a small reduction in the net thrust (0.3%) and a slight reduction in TSFC (0.1%) due to the combined effects of reducing the fuel flow and diverting energy from the bleed air to the fuel. When the benefit of fuel cooling is applied toward reducing the amount of HPT cooling air, then the engine bypass ratio can be increased by 14% at the sea level static design point, resulting in a 0.7% TSFC benefit at the supersonic cruise condition. It should be noted that for either case, the heat transferred to the fuel represents less than 50% of its total heat sink potential.

A further study was performed to evaluate the cooling concept impact at subsonic speeds. The impact of reducing the HPT vane and blade cooling air temperature by 200 F was evaluated at the 0.9M/36K subsonic cruise condition. Table 2 shows the effect of fuel cooling on HSCT engine performance for the two approaches. As previously for supersonic cruise, for increased engine lifetime,

the amount of high-pressure-turbine cooling is maintained at the baseline flow rate, resulting in lower metal temperatures. For improved fuel economy, the HPT cooling is reduced to 75% of the baseline flow while metal temperatures and, therefore, turbine life remain unchanged from the baseline engine. In both instances, the HPT rotor inlet temperature is maintained constant.

In the case directed toward increasing lifetime, the heat added to the fuel from cooling the turbine cooling air increased the lower heating value of the fuel by 3.5% and reduced the specific fuel consumption by 0.4%. In the case aimed at improving fuel economy, the reduction in HPT cooling air flow was used to increase the engine bypass ratio by 14% at the sea level static design point. This cycle produced a 1.6% reduction in subsonic cruise fuel consumption.

Table 2 - Effect of Fuel Cooling on HSCT Engine Performance at 0.9M/36K Subsonic Cruise (Change from Baseline)

	Increased Lifetime	Improved Fuel Economy
HPT Cooling Air, % of Baseline	100	75
Increase in Fuel Heating Value, Btu/lb	650	475
TSFC Change, %	- 0.4	- 1.6

An additional analysis was performed to evaluate the effects of the catalytic heat exchanger/reactor (CHER) design on component weight, pressure drop and thermal performance. Both the heat exchanger size and internal core geometry were varied to allow a determination of the relationship between weight and pressure loss, at a constant thermal effectiveness. The results were used to identify a design concept that will limit the maximum air-side pressure loss to approximately 5%. The resulting weight of the heat exchanger core will be approximately 160 lb, representing an approximate 1% increase in the engine weight. The impact of increased weight is considered in the economic analysis performed as part of this study.

COOLING CONCEPT DEFINITION

Based on the HSCT cycle analysis, the thermal management concept selected for increasing component life in the engine hot section involves cooling a portion of the high-pressure-compressor discharge air (T_3) with 80% of the fuel in an external catalytic heat exchanger reactor (CHER). The results of the initial evaluation indicate that the desired 200 F bleed air temperature reduction can be attained, and that all turbine components can be cooled with air at the same condition. The CHER pressure loss depends on the size of the heat exchanger, and the analysis showed that a CHER core weighing approximately 160 lb could provide the desired cooling with a total pressure loss of approximately 5-6% (including plumbing losses).

Current and state-of-the-art turbine cooling concepts employ different methods for cooling various stages in the turbine, with very significant differences between the first vane and subsequent downstream stages. Traditional vane cooling concepts utilize upstream-facing orifices in the leading edge (showerhead cooling concept) to inject a film of cooling air into the hot gas stream. In conventional arrangements, the supply air at the compressor discharge pressure (P_3) satisfies the requirements for vane cooling, with the pressure loss in the burner balancing the coolant pressure loss in the vane cooling passages. In a fuel-cooled thermal management system, the impact of the added cooling-air pressure loss across the CHER and external plumbing must be examined with regard to use in the turbine first-stage vanes, which require air supply pressure in excess of the total pressure of the burner discharge.

The required supply pressure for the first-stage vane must match the cycle requirement imposed by the burner pressure loss, while the supply condition at the first-stage turbine blade can be at a substantially lower pressure, because of the flow acceleration and static pressure drop across the vane stage. These requirements imply that air at a single supply pressure does not present a viable design approach, and innovation is required to satisfy the first-stage vane cooling problem. To satisfy the increased pressure requirement, an approach involving additional compression of the vane cooling air was evaluated, with the objective of identifying the weight and power trades. A thermal management system architecture, including an auxiliary compressor for pumping vane coolant, was defined, and a simulation was configured to evaluate the system.

The selected system is shown in Figure 1, illustrating the various components. In this system concept, cooling air for the turbine is extracted from the core and cooled in two separate paths. Air for the first-stage turbine vane is cooled and then compressed to a sufficient pressure level for re-insertion into the vane cooling system. The compressor pressure ratio is selected to compensate for pressure loss in the heat exchanger and attendant plumbing system. Power to drive the compressor is extracted from the engine shaft. Cooling air for the blades is not pumped, and is supplied at the pressure level available from the catalytic heat exchanger reactor (CHER). Efforts were directed at refining the concept for providing turbine vane coolant to minimize component sizes. The refined concept entails supercooling a portion of the vane cooling air with fuel, supercharging it using an auxiliary compressor, and mixing it with diffuser bleed air (at P_3 and T_3) to produce the required amount of coolant at the desired conditions.

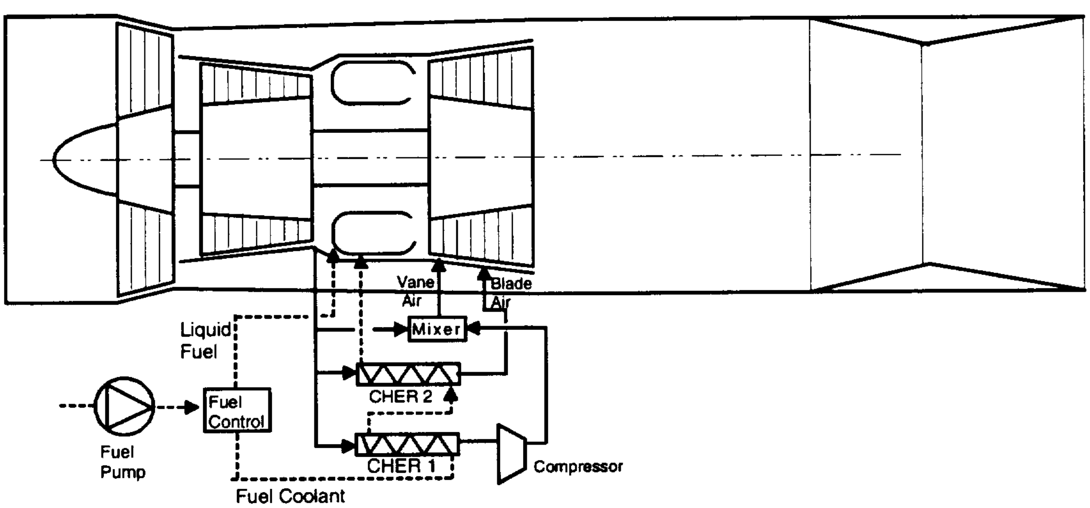

Figure 1. Improved Concept for Fuel Thermal Management of Turbine Cooling Air

Preliminary studies indicate that sufficient heat sink is available in the fuel to allow supercooling of a fraction of the airflow, and the net result is a significant reduction in the size and power requirement of the external compressor. Since the cooling system component sizes are directly related to the selected flow split, conceptual design and optimization trade studies of the cooling system were conducted to evaluate the sensitivities of the size, weight, and power demand of the various components.

To design and evaluate the integrated thermal management system illustrated in Figure 1, a model was formulated and a corresponding simulation was developed. This simulation includes the major components in the system, including the heat exchangers, compressor, and mixer required to provide cooled air at the desired conditions. The model of the thermal management system is illustrated in Figure 2, and comprises a series of counterflow heat exchanger modules.

As shown in Figure 1, a portion of the air for the first turbine vane is cooled and then compressed and mixed with the remainder of the required flow to yield the desired coolant temperature. Splitting the flow and supercooling the pumped fraction allows a reduction of the required pumping power. Another potential system enhancement is to incorporate an ejector into the mixer, to use the cooled stream to pump the hot stream. Considering these various options, it becomes apparent that with several design variables (i.e., flow split, heat exchanger performance and weight, compressor size and power requirements, and performance and weight of the mixer), there is an optimum combination that minimizes system weight/power extraction.

The initial results of the trade study indicated that the required flow split for cooling the first-stage vane is approximately 35% supercooled air mixed with the remaining air at compressor discharge conditions. The pumping requirement was initially estimated to be in the range of 150 - 200 hp, and is dependent on the efficiency of the mixing process. It is assumed that injection and mixing of the cooled and uncooled compressor bleed air streams occurs in a distributed vane ejector, and a model for such an ejector/mixer component was incorporated into the thermal management system simulation.

The thermal management system, as illustrated in Figure 2, is composed of a series of counterflow heat exchanger modules arranged in two separate arrays. The first array of four CHER modules provides coolant for the first-stage turbine vanes, while the second array of six modules provides cooled air for the remainder of the turbine. Evaluation of the thermal management model indicates that the

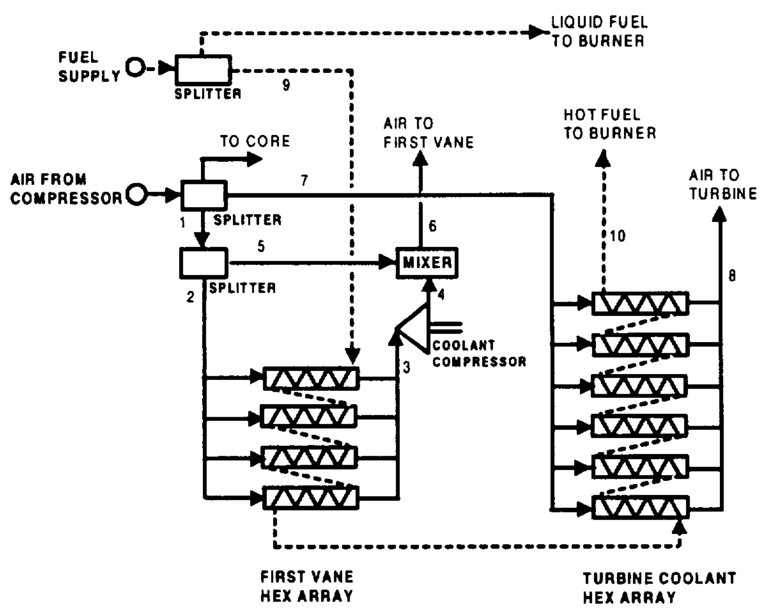

Figure 2. Conceptual Design Arrangement for Cooling Trade Study

desired cooling can be provided with pressure losses within the allowable limits of the various turbine stages.Conceptual design of the required auxiliary compressor was performed, and its weight was estimated. In addition, weight estimates were performed for all for all of the additional thermal management system components, including the heat exchangers, manifolds, mixer, and air ducts. The total weight of the thermal system is estimated to be 360 lb.

ECONOMIC ANALYSIS

A first-order economic analysis was performed to estimate the value endothermic technology may bring to the HSCT application. Estimates of weight, specific fuel consumption, manufacturing cost and maintenance cost were used to determine airline direct operating cost plus interest (DOC+I). Airline direct operating cost plus interest (DOC+I) is used to provide a measure of acceptability of new technologies in the airline industry. DOC+I comprises fuel costs, engine maintenance costs, airframe maintenance costs, flight crew costs, hull insurance, depreciation (a function of engine and airframe price) and interest.

Estimates of changes in specific fuel consumption (SFC), engine weight, maintenance cost and purchase price have been made for the new thermal management system concept. Influence coefficients are used to equate each of these changes to a change in DOC+I. DOC+I influence coefficients were generated for a 300 passenger, Mach 2.4 Technology Concept Airplane (TCA) with the selected engine cycle. A 3500 nm economic mission was assumed. Two possible benefits of applying the technology were evaluated, namely to increase lifetime and to improve fuel economy, showing the possible range of costs or benefits this technology may bring to the aircraft application. The influence coefficients used for the study were developed for the HSCT by the Propulsion System Evaluation Team for the HSR program. The TCA is sized to meet take-off field length, climb and take-off noise requirements for a 5000 nm mission with a subsonic cruise leg which is 15% of the design range. Although the HSCT is designed to have the capability to fly 5000 nm in 5.3 hr with a full passenger load, its average mission length on a day-to-day basis will be significantly shorter. A typical 4 hr economic mission of 3500 nm with a 20% subsonic leg was selected in defining the HSCT's airline DOC+I. Economic ground rules for this study are shown in Table 4, and are also traceable to the CPC effort.

Table 4.- Ground Rules for Economic Study

Year Dollars	1995
Fuel Price	$0.63/gallon
Utilization	1030 flights/year
Interest rate	9.00%
Economic life	20 years
Resale value	10%
Engine Spares	23%

Historical trend data were used to estimate engine cost and maintenance cost. Engine cost estimates are limited to the endothermic cooling system itself and do not include placement and packaging issues which will need to be addressed due to the size of this system. As stated previously, two methods for applying endothermic reaction technology to the HSCT were considered in this study, namely improved life, and improved fuel economy. The "improved life" approach requires minimal change to the engine cycle. The HSCT has a turbine blade life goal of 9000 hot hours. A 200 F lower metal temperature in the high pressure turbine (HPT) translates into longer blade life and lower engine maintenance cost. Based on maintenance cost trends, a 200 F temperature reduction will result in a 35% increase in the HPT airfoil life, which will effect a 4.5% savings in engine maintenance cost.

The contributors to DOC+I are summarized in Table 5, and rolled up into an overall airline DOC+I for a total system evaluation. The changes in engine weight and purchase price are estimated, and are due to the weight and cost of the thermal management system components. The "improved fuel economy" case demonstrates the potential benefits of optimizing the thermal management system with the engine cycle.

Table 5 - Overall DOC+I for Airline

Parameter	Improved Life: Change	Improved Life: Δ DOC+I	Improved Fuel Economy: Change	Improved Fuel Economy: Δ DOC+I
SFC @ supersonic (M=2.4)	-0.1%	-0.09%	-0.7%	-0.66%
SFC @ subsonic (M=0.9)	-0.4%	-0.13%	-1.6%	-0.53%
Weight	360 lb	+0.53%	360 lb	+0.53%
Maintenance cost	-4.5%	-0.54%	TBD	TBD
Purchase price	$197,300	+0.15%	$197,300	+0.15%
Overall DOC+I		-0.08%		-0.51%

This first-order economic analysis of the value of endothermic reaction technology in the HSCT indicates that significant monetary savings can be realized due the projected improvement in fuel economy. Although attendant savings would accrue from the corresponding improvement in the life of the high-pressure turbine, the key benefit of fuel cooling to the turbine would be to provide enabling technology for achieving the life goal with available materials.

SUMMARY

This study identifies the benefits that can be achieved if the high temperature endothermic heat sink capability of Jet A fuel is applied to provide additional cooling for the engines in the HSCT aircraft. Significant improvements in fuel economy and increased engine life can be achieved, with the increased cooling capability providing reduced material temperatures. Economic evaluation of the impact of these benefits on the HSCT show net reductions in direct operating costs accrued by the use of fuel cooling, the specific amount depending on the method of applying the cooling potential to the engine system.

Several critical issues have been identified with regard to application of endothermic reaction technology in the HSCT aircraft. These include (a) development of high temperature, high pressure fuel-air heat exchangers with thermal-structural capability adequate to satisfy the safety and long-life requirements of commercial flight systems, and (b) definition of reliable, affordable and maintainable supercritical fuel systems that will satisfy the operability requirements of the HSCT application.

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The success of strategies for controlling emissions and enhancing performance in High Speed Research applications may be increased by more effective utilization of the heat sink afforded by the fuel in the vehicle thermal management system. This study quantifies the potential benefits associated with the use of supercritical preheating and endothermic cracking of jet fuel prior to combustion to enhance the thermal management capabilities of the propulsion systems in the High Speed Civil Transport (HSCT). A fuel-cooled thermal management system, consisting of plate-fin heat exchangers and a small auxiliary compressor, is defined for the HSCT, integrated with the engine, and an assessment of the effect on engine performance, weight, and operating cost is performed. The analysis indicates significant savings due a projected improvement in fuel economy, and the potential for additional benefit if the cycle is modified to take full advantage of all the heat sink available in the fuel.

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